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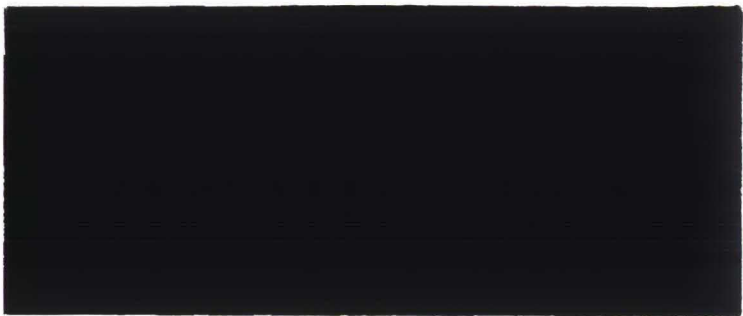
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STRONGLY REGULAR GRAPHS INDUCED BY  
POLARITIES OF SYMMETRIC DESIGNS

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STRONGLY REGULAR GRAPHS INDUCED BY POLARITIES OF SYMMETRIC DESIGNS

by

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ABSTRACT. We study symmetric designs with a polarity for which the graph induced by the absolute points and the graph induced by the non-absolute points both are strongly regular. The main result is that all parameters can be expressed in terms of only one parameter.

## INTRODUCTION.

Throughout, we shall assume that  $A$  is the  $(0,1)$  incidence matrix of a symmetric  $2-(v,k,\lambda)$  design  $D$  with a polarity with  $v_1 (\neq 0)$  absolute points and  $v_2 = v - v_1 (\neq 0)$  nonabsolute points. So  $A$  takes the form:

$$A = \begin{bmatrix} A_1 & C \\ C^T & A_2 \end{bmatrix},$$

where  $A_1$  and  $A_2$  are symmetric matrices,  $A_1$  has ones on the diagonal and  $A_2$  has zeros on the diagonal. Thus  $A_1 - I$  and  $A_2$  are adjacency matrices of graphs  $\Gamma_1$  and  $\Gamma_2$ , say. We call  $\Gamma_1$  and  $\Gamma_2$  the graphs *induced* by the polarity of  $D$ . The above decomposition of  $A$  is called the *polar decomposition*. A polar decomposition is *regular* if  $\Gamma_1$  and  $\Gamma_2$  are regular, and *strongly regular* if  $\Gamma_1$  and  $\Gamma_2$  are strongly regular, complete or empty. The incidence structure of absolute points and nonabsolute blocks, given by the matrix  $C$ , is called the *polar structure* of the design  $D$ .

We assume that  $D$  is nontrivial, i.e.  $0 < \lambda < k-1 < v-2$ . Polar decompositions of trivial designs are obvious and not very interesting.

In the present paper we study strongly regular polar decompositions. It is, in a certain sense, an extension to a paper on strongly regular graphs with strongly regular decompositions by the first two authors [1]. The subject is motivated by the following example. Let  $D$  be the design of points and hyperplanes of  $PG(n,4)$  ( $n \geq 2$ ). Then the graphs induced by the unitary polarity are strongly regular (see for instance [3]). The parameters for this example are:

$$v = \frac{4^{n+1}-1}{3}, \quad k = \frac{4^n-1}{3}, \quad \lambda = \frac{4^{n-1}-1}{3}, \quad v_1 = \frac{2^{2n+1}-(-2)^{n-1}}{3}.$$

We shall prove that all parameters of a strongly regular polar decomposition can be expressed in terms of only one parameter  $a$ . If  $a$  is a power of  $-2$  we find the values above, but unfortunately, other values of  $a$  for which no examples are known, remain feasible.

For strongly regular  $\Gamma_i$  ( $i = 1, 2$ ) the parameters are denoted by  $v_i$ ,  $k'_i$ ,  $\lambda_i$  and  $\mu_i$ , and the eigenvalues of  $A_i$  by  $k_i$ ,  $\rho_i$  and  $\sigma_i$ , such that  $|\rho_i| \geq |\sigma_i|$ . Note that  $k_1 = k'_1 + 1$  and  $k_2 = k'_2$ . The multiplicity of  $\sigma_i$  is denoted by  $\varphi_i$ . If  $\Gamma_i$  is complete or empty we put  $\varphi_i = v_i - 1$  ( $\rho_i$  disappears).

#### PRELIMINARIES.

The following three Lemmas are the analogues of 2.2, 2.4 and 2.5 of [1]. Since the proofs are the same, we omit them here.

**Lemma 1.** Suppose  $\Gamma_1$  is regular of degree  $k'_1 = k_1 - 1$ . Then

$$\left| \frac{k_1 v - v_1 k}{v - v_1} \right| \leq \sqrt{k - \lambda}.$$

Equality holds if and only if the polar decomposition is regular.

Note that for the polar decomposition to be regular  $k - \lambda$  (the order of  $D$ ) must be a square.

For a regular polar decomposition we define  $k_2$  to be the degree of  $\Gamma_2$  and

$$(1) \quad a = \frac{k_1 v - v_1 k}{v - v_1}.$$

Then we easily have

$$(2) \quad a = k_1 + k_2 - k = \pm \sqrt{k - \lambda}, \quad |a| \geq 2.$$

So  $a$ ,  $-a$  and  $k$  are the eigenvalues of  $A$  with multiplicities  $\varphi$  (say),  $v - 1 - \varphi$  and 1, respectively.

**Lemma 2.** Suppose  $A_1$  has eigenvalues  $k_1$ ,  $\sigma_1$  and  $\rho_1$  ( $|\sigma_1| \leq |\rho_1|$ ) with multiplicities 1,  $\varphi_1$  and  $v_1 - 1 - \varphi_1$  ( $1 \leq \varphi_1 \leq v_1 - 1$ ), respectively. Let the

polar decomposition be regular. Then  $A_2$  has eigenvalues  $k_2$ ,  $-\sigma_1$ ,  $-\rho_1$ ,  $a$ ,  $-a$  with multiplicities 1,  $\varphi_1$ ,  $v_1-1-\varphi_1$ ,  $\varphi-v_1$  and  $v_2-\varphi$ , respectively. Also  $|\sigma_1| \leq |\rho_1| \leq |a|$ , and  $|\sigma_1| \neq |a|$ .

**Lemma 3.** With the hypotheses of Lemma 2, the polar decomposition is strongly regular if and only if one of the following occurs.

- i.  $v_1 = v_2 = \varphi$ ,
- ii.  $\rho_1 = a$ ,  $v_1 = \varphi$ ,
- iii.  $\rho_1 = -a$ ,  $v_2 = \varphi$ ,

It is easy to see that if ii occurs for a matrix  $A$ , then iii occurs for the complementary case, that is for the design with incidence matrix  $(J$  denotes the all-one matrix).

$$J = \begin{bmatrix} A_2 & C^T \\ C & A_1 \end{bmatrix},$$

Note that Lemma 3 also applies if  $\Gamma_1$  is complete or empty (the conditions  $\rho_1 = \pm a$  are meaningless in this case). Next we show that case i does not occur.

**Lemma 4.** A strongly regular polar decomposition with  $v_1 = v_2 = \varphi$  does not exist.

**Proof.** Assume  $v \geq 2k$  (otherwise consider the complement). Trace  $A = v_1 = \varphi = k + \varphi a - (v-\varphi-1)a$  implies  $k = v_1 - a$ . Hence, by (1) and (2),  $k_1 = k_2 = v_1/2 = v_2/2$ . Therefore, since  $\Gamma_2$  is strongly regular,  $k_2(k_2 - \lambda_2 - 1) = \mu_2(v_2 - k_2 - 1) = \mu_2(k_2 - 1)$ . This implies  $\mu_2 = 0 \pmod{k_2}$ , hence  $\Gamma_2$  is complete bipartite, so  $\rho_2 = -k_2$ . This is impossible, since then, by Lemma 2,  $|a| \geq |\rho_2| = k_2 = v_2/2 = v/4$ , which is a contradiction to  $a^2 < k \leq v/2$  and  $|a| \geq 2$ .  $\square$



## MAIN THEOREM.

**Theorem 5.** If  $D$  has a strongly regular polar decomposition then  $a \equiv 4 \pmod{6}$ , and, up to taking complements, all other parameters are expressible in terms of  $a$  as follows:

$$v = \frac{1}{3}(16a^2 - 1), \quad k = \frac{1}{3}(4a^2 - 1), \quad \lambda = \frac{1}{3}(a^2 - 1),$$

$$v_1 = \varphi = \frac{1}{3}(2a+1)(4a-1), \quad v_2 = \frac{2}{3}a(4a-1),$$

$$k'_1 = k_1 - 1 = \frac{2}{3}(a-1)(a+2), \quad k'_2 = k_2 = \frac{1}{3}a(2a-1),$$

$$\rho_1 = -\rho_2 = a, \quad \sigma_2 = -\sigma_1 = \frac{a}{2},$$

$$\varphi_1 = \varphi_2 = \frac{8}{9}(a-1)(2a+1),$$

$$\mu_1 = \frac{1}{6}(a-1)(a+2), \quad \lambda_1 = \frac{1}{6}(a^2 + 4a - 2),$$

$$\mu_2 = \frac{1}{6}a(a+2), \quad \lambda_2 = \frac{1}{6}a(a-1).$$

**Proof.** We may restrict ourselves to case ii of Lemma 3. By this result we can express all parameters in terms of  $k$  and  $a$  only. We have  $\lambda = k - a^2$ , and hence, using  $\lambda(v-1) = k(k-1)$ :

$$v = \frac{k^2 - a^2}{k - a^2}.$$

Trace  $A = v_1 = \varphi = k + \varphi a - (v-1-\varphi)a$  yields

$$v_1 = \frac{k(k+a)(a-1)}{(k-a^2)(2a-1)}, \quad v_2 = \frac{a(k+a)(k+1-2a)}{(k-a^2)(2a-1)}.$$

Next, using (1) and (2), we find

$$k_2 = \frac{ak}{2a-1}, \quad v_2 - k_2 - 1 = \frac{k(a+1)(a-1)^2}{(k-a^2)(2a-1)}.$$

Since  $k - a^2 = \lambda > 0$  and  $|a| \geq 2$  it follows that  $0 < k_2 < v_2 - 1$ , so  $\Gamma_2$  is not the empty graph or the complete graph. Moreover,  $2a-1$  divides  $k$ . Define  $x = k/(2a-1)$ , then  $k_2 = ax$  and  $a$  and  $x$  have the same sign. By use of  $\rho_2 = -a$  (by Lemma 2 and 3) and  $(k_2 - \rho_2)(k_2 - \sigma_2) = (k_2 + \rho_2 \sigma_2)v_2$  (because  $\Gamma_2$  is strongly regular) we find after some computation:

$$\sigma_2 = \frac{a(ax+a-2x)}{2ax-x-1}.$$

Define

$$d = 4\sigma_2 - 2a + 3 = \frac{4a^2 + 2a - 3x - 3}{2ax - x - 1},$$

then  $d \geq 0$ , since  $d \leq -1$  would imply  $(2a-1)(a+1) \leq x(1-a) < 0$ , which contradicts  $|a| \geq 2$ . Moreover, using  $2ax - x - 1 = k - 1 \geq a^2$ , we have

$$d \leq 4 + \frac{2}{a} - \frac{3(x+1)}{2ax-x-1} < \begin{cases} 4 + \frac{2}{a} \leq 5 & \text{if } a \text{ and } x \text{ are positive,} \\ 4 - \frac{3}{2a-1} < 5 & \text{if } a \text{ and } x \text{ are negative.} \end{cases}$$

Since  $d$  is odd we can conclude that  $d = 1$  or  $d = 3$ . If  $d = 1$ , then  $x = 2a-1$  and  $v_1 = (2a-1)(4a^2 - 3a + 1)/(3a-1)$ , which is no integer. Hence  $d = 3$ , so

$$x = \frac{2a+1}{3}, \quad \sigma_2 = \frac{a}{2}, \quad a \equiv 4 \pmod{6}.$$

All other parameter now follow in a straightforward manner. □

If  $a = (-2)^{n-1}$  we find the parameters of the example given in the introduction. No other examples are known. This leaves  $a = 10$  (D is a  $2-(533, 133, 33)$  design) as the smallest unsolved case. By Theorem 5, only for  $a = -2$  one of the graphs induced by the polarity is complete or empty. For  $a = -2$ , however, the structure is unique. So  $\text{PG}(2, 4)$  with its unitary polarity and the complement provide the only strongly regular polar decomposition for which one of the induced graphs is empty or complete. In this case the polar structure is  $\text{AG}(2, 3)$ , the affine plane of order 3. If  $|a| > 2$ , it can be shown (by similar, but less complicated, arguments as for Theorem 2.8 of [1]) that the polar structure is a strongly regular design (see [2] for definition and notation) with parameters

$$(3) \quad (n_1, S_1, a_1, b_1, n_2, S_2, a_2, b_2) = (v_1, k-k_1, \lambda-2-\lambda_1, \lambda-\mu_1, v_2, k-k_2, \lambda-\lambda_2, \lambda-\mu_2),$$

and that, conversely, a strongly regular design whose parameters satisfy (3) with  $v_1$ ,  $k$ ,  $k_1$  etc. as given in Theorem 5, is the polar structure of some symmetric design with a strongly regular polar decomposition.

A symmetric design with a polarity can be seen as a strongly regular graph for which loops are admitted. More precisely, if we allow loops in graphs, a strongly regular graph is a simple strongly regular graph or a symmetric design with a polarity. In this more general setting, a strongly regular graph with strongly regular decomposition either belongs to the case without loops treated in [1], or is a design with a strongly regular polar decomposition. This can be proved as follows. For a strongly regular decomposition of a symmetric design with a polarity it follows by eigenvalue arguments as in Lemma 3, that if  $\Gamma_1$  is a symmetric design with a polarity, then so is  $\Gamma_2$ . This, however is impossible by Rahilly [4]. Thus both  $\Gamma_1$  and  $\Gamma_2$  must be strongly regular graphs without loops, so we have a strongly regular polar decomposition.

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